

# Fragmentation of Strange Quark Matter in Astrophysical Events

J.E. Horvath<sup>1</sup> L. Paulucci Marinho<sup>2</sup>

<sup>1</sup>*Instituto de Astronomia, Geofísica e Ciências Atmosféricas Universidade de São Paulo, R. do Matão 1226, Cidade Universitária 05579-010 São Paulo, SP Brazil*

<sup>2</sup>*Universidade Federal do ABC, Rua Santa Adélia, 166, 09210-170 Santo André, SP Brazil*

## 1 Introduction

The presence of exotic quark matter among cosmic ray primaries has been a subject of experimental and theoretical studies for many years. It is safe to say that a milestone concerning this issue was the detection of the very intriguing “Centauro” events [1], later interpreted as the explosion of a quark blob by Björken and Mc Lerran [2]. Over the years, many reports have been published and some retracted [3]. One of the latest examples of this class of events has been recently described by Basu et al. [4]. The importance of these phenomena for the knowledge of hadronic physics and its occurrence in nature can not be overstated.

It is clear that the idea of quark blobs coming from outer space needs an appraisal in terms of production, ejection and survival of quark matter from its original site to the detectors. Since the last 30 years a stable form of that matter, the so-called strange quark matter (SQM) [5] has been studied and discussed. SQM, and its finite- $A$  version (strangelets) is particularly suitable as a candidate for the primaries and expectations for its direct detection (for instance, in the AMS-02 experiment [6] have been published elsewhere [7]. However, there are some important caveats concerning the very process of fragmentation of SQM (assuming it is the true ground state of hadronic interactions), with the corresponding consequences for the total flux. We shall discuss below some of these issues, focusing on the physics of fragmentation. The goal would be to check whether a high enough strangelet flux is generated, independently of the acceleration processes [8] within the known models widely applied to nuclei.

## 2 Strangelets from SS mergers, supernovae or both?

Strange stars are the astrophysical realization of the SQM hypothesis. These should mimic ordinary neutron stars in many respects, and a lot of work has been performed

to distinguish them through some clear signature. This is far from easy, although for the moment we must assume that strange stars are present and form shortly after a collapse/supernova event [9].

The possibility that the very birth of strange stars ejects some SQM into the ISM has been considered long ago [9][10]. The general picture relies on the development of instabilities ending in a fully turbulent propagation front [11], much in the same way as it is thought to happen in ordinary thermonuclear supernovae [12]. However, recent work [13] did not find any SQM ejection, at least within the explored physical conditions. Since (collapse) supernovae are very common, even a tiny fraction of bulk SQM would populate the galaxy with primaries and deserves consideration.

In a paper addressing this question, namely what happens if bulk SQM is injected swiftly as a result of the propagation of a combustion (which may be entangled to cause of the supernova [9]), we [14] have studied the fragmentation of SQM on their way out by collisions with oxygen nuclei using a simple spallation scheme [15]. Strangelets lose mass and kinetic energy in most cases, giving rise to a scaling law for the final mass  $m_F$  in terms of its initial value  $m_i$  of the form

$$\left(\frac{m_F}{m_i}\right) = \left(\frac{\Delta_0 E_b}{m_p E_{O_i}}\right)^{1/2(D-1)}, \quad (1)$$

where  $\Delta_0$  is a scale for effective spallation of a fragment with that mass number,  $E_b$  is the binding energy released in the process,  $E_{O_i}$  is the initial energy of an oxygen nucleus and  $D$  is a dimensionless quantity generally  $\geq 1$  containing the radius of the strangelet and additional quantities. The bottom line of that calculation is that there is a real chance to obtain strangelets in the range  $A \sim 10^3$  provided the spallation with oxygen nuclei is efficient enough. Of course, this does not address the injection mass spectrum, that is, the fragmentation prior to interactions with the oxygen nuclei, a subject that will be considered soon.

An attempt to refine the crude model of Vucetich and Horvath [14] has been made in the last years [16]. Basically the model replaced the empirical Boyd-Saito [15] with an abrasion-ablation scheme of the type usually employed in the GEANT4 algorithm and similar procedures. We found that at around  $E/A \sim 10 \text{ MeV}/A$  the spallation (abrasion) quickly dominates the fusion and scattering cross-sections, giving rise to a much moderate downsizing of simulated strangelet-nitrogen collisions. Therefore, it is likely that the first models overestimated the reprocessing of strangelets and  $A \sim 10^2 - 10^3$  fragments could be produced only if the initial baryon number was not very high. Thus, the initial mass distribution becomes an essential ingredient.

The idea of fragmentation of bulk ejected SQM itself was never considered in depth because the binding energy of the former always increases with baryon number  $A$ . At first sight, producing fragments out of a big chunk would go against energetics because the process must work “uphill”. Madsen [17] equated the gravitational energy to the surface energy to estimate that around  $A \sim 10^{38}$  the SQM should break up in

chunks of that  $A$ . His picture of big nuggets orbiting a SS lead him to identify orbital collisions as the mechanism to further fragment the chunks into  $A \sim 10^3$  strangelets, that is, a very substantial reprocessing indeed.

In complete analogy with bulk nuclear matter, it is expected, however, that a consideration of the free energy of the system (not just the binding energy) indicates the fragmentation point and also the mass distribution of the fragments. The physical situation of any ejected SQM in bulk corresponds to an expansion and cooling of the system, and therefore excluded volume at the fragmentation point and vacuum “melting” should be important as well. Note that this is independent of reprocessing by collisions. Moreover, such a situation would be encountered in the first moments after a supernova shock breakout, but also in the situation of ejection at the merger of two compact strange stars [18]. The latter process could eject as much as  $10^{-4}M_\odot$  in the form of SQM, but this would produce either planetary mass chunk(s) or require very efficient reprocessing, as explained above, to later match the reported CR primary range. We shall now present the results of a calculation intended to explain the fragmentation and the mass distribution of the fragments, without considering further collisions or acceleration.

### 3 Multifragmentation of SQM

Statistical multifragmentation models are known to reproduce the fragment distribution of ordinary heavy nuclei and can be applied whenever the temperature  $T$  is of the order of the binding energy. In the grand canonical ensemble, the partition function reads [19]

$$\omega_A = V \left( \frac{mT}{2\pi} \right)^{3/2} e^{-f_A/T}, \quad (2)$$

with  $f_A$  the internal free energy of the fragment

$$f_A = -WA + \sigma A^{2/3} + CA^{1/3}, \quad (3)$$

representing the bulk, surface and curvature terms respectively. Performing the Fourier transform of eq.(2)  $\mathcal{Z}$ , and recalling that

$$p(T, \mu) = T \lim_{V \rightarrow \infty} \frac{\ln \mathcal{Z}(V, T, \mu)}{V}, \quad (4)$$

the problem of the fragmentation is reduced to finding the singularities of the isobaric partition function, yielding the gas and liquid pressures as

$$p_g(T, \mu) = T \left( \frac{mT}{2\pi} \right)^{3/2} \left\{ z_1 e^{\frac{\mu - bp_g}{T}} + \sum_{A=2}^{\infty} A^{3/2} e^{[(\nu - bp_g)A - \sigma A^{2/3} - CA^{1/3}]/T} \right\}, \quad (5)$$

$$p_l(T, \mu) = \frac{\nu}{b}, \quad (6)$$

where  $\nu = \mu + W$  is the (shifted) chemical potential. The fragmentation spectrum is obtained from the derivatives of the pressure assuming chemical equilibrium. However, when these quantities were calculated for SQM within the MIT bag model framework and in the color-flavor-locked (CFL) state [20], the surprising result that the peak of the fragments happens in the region  $A \ll 1$  was obtained in all cases, even introducing a simple Van der Waals approximation. This may be due to the hidden assumption about a constant energy of the vacuum (represented by an MIT value  $B$ ). However, physical considerations can be made in favor of a “melting” of the vacuum picture: a fraction of the vacuum energy is being used to create the surfaces and curvature energies, therefore there should be an energy density difference between the phases

$$\begin{aligned} W_l &= W_0 + Bv_{liq}, \\ W_g &= W_0 + Bv_{gas}. \end{aligned}$$

After this correction, the distribution shifts to higher values of  $A$ . We have normalized the probabilities to a total of  $10^4 M_\odot$  as expected from the above considerations [21]. The masses of the fragments (strangelets) reach higher values when progressively higher temperatures are considered (Fig. 1). However, as is well-known the stability of the strangelets diminishes with rising temperature, and an increasing number of fragments should decay into ordinary hadrons

## 4 Conclusions

From the calculations performed in a series of studies we may conclude that either SQM does not like to fragment, or if it does an overwhelmingly large fraction of the original baryon number would be ultimately go into ordinary particles, not strangelets. A similar calculation by Biswas et al [22] has pointed out the sensitivity to the treatment of the binding energy dependence, while the results above become odd without a substantial role of the vacuum melting. If the fragmentation destroys most of strangelets, the flux of exotics in CRs could be minuscule. Actually, the (optimistic) expression for the latter given by Madsen [23]

$$F = 5 \times 10^5 (m^2 \text{ yr sterad})^{-1} \times R_{-4} \times M_{-2} \times V_{100}^{-1} \times t_7, \quad (7)$$

with  $R_{-4}$  the rate of mergers in units of  $10^{-4} \text{ yr}^{-1}$ ,  $M_{-2}$  the ejected mass going into strangelets in units of  $10^{-2} M_\odot$  should be multiplied by an efficiency factor of at

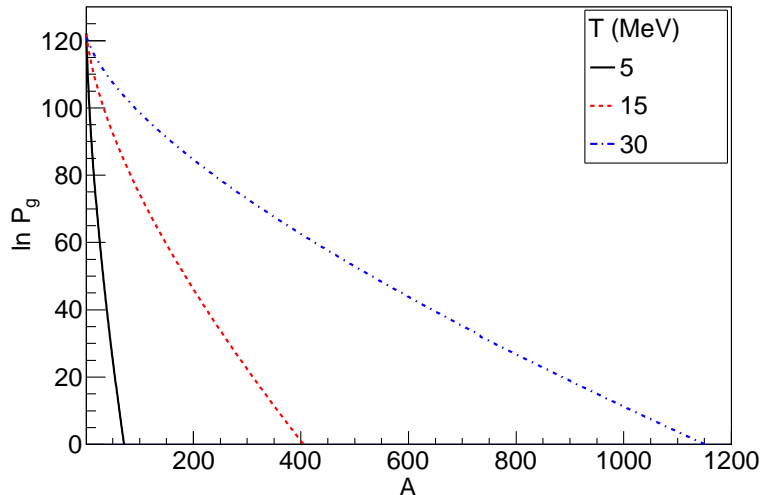


Figure 1: The distribution function of the fragments (strangelets) normalized to  $10^{-4}M_{\odot}$  for three different values of the temperature (indicated). Fragmentation at higher temperatures favor a tail of heavier particles, but also destabilizes the small  $A$  strangelets. As a result, the net number of surviving strangelets decreases at higher temperatures.

least  $10^{-5}$  representing the strangelet fragility under decays. This is independent of the possibility that the ejection could indeed be *zero* ([18]) in these events. Adding the caveats already made in the supernova case, we conclude that if strangelets are positively detected after all, the fragmentation should proceed out of equilibrium, a possibility yet to be explored.

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